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Published in:

Proceedings of the 41st International Conference on Infrared, Millimeter and Terahertz Waves, IRMMW-THz 2016

Link to article, DOI:

[10.1109/IRMMW-THz.2016.7758901](https://doi.org/10.1109/IRMMW-THz.2016.7758901)

Publication date:

2016

Document Version

Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):

Stefani, A., Lwin, R., & Argyros, A. (2016). Hybrid antiresonant metamaterial waveguides for THz and IR. In *Proceedings of the 41st International Conference on Infrared, Millimeter and Terahertz Waves, IRMMW-THz 2016* [7758901] IEEE. International Conference on Infrared, Millimeter and Terahertz Waves <https://doi.org/10.1109/IRMMW-THz.2016.7758901>

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Hybrid Antiresonant Metamaterial Waveguides for THz and IR

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Abstract—We report on a novel waveguide concept which combines antiresonant and metamaterial guidance. The guidance is achieved in the hollow core and loss as low as 2.3 dB/km are theoretically achievable in the THz frequency range. Both purely antiresonant and antiresonant metamaterial fibers have been fabricated and characterized. The realized metamaterial fiber has been simulated to have 0.3 dB/m loss at 0.3 THz.

I. INTRODUCTION

CONTINUOUS interest is going into novel, better performing and multifunctional waveguides. This applies to the entire radiation spectrum, but more intensively in the wavelength spectrum spanning from the mid-IR to the mm waves. Here, the current technology doesn't provide any solution as optical fibers for the visible and near-IR wavelengths.

Hollow waveguides are very promising for this purpose, since they, at least partially, remove the issue of material loss. A particular class of this waveguides has caught the attention of researchers in the last years, i.e. antiresonant fibers [1-2]. The simple structure is one of the main features of these waveguides; nonetheless they offer very good guiding properties. A different approach that has been looked into, mostly for THz frequency radiation, is to combine subwavelength metal and dielectric into waveguides [3]. At these frequencies, the loss of subwavelength metal structures are not a limiting factor as they are for short wavelengths such as the visible and near-IR. However, not many experimental results on metamaterial waveguides have been so far reported. Combining the properties of antiresonant guiding and metamaterial structures, we propose a new type of waveguide, which has potential for record low loss. The proposed fiber includes hollow bodies, which can also be used for sensing, and includes metal wires, for potential multifunctional purposes. These features widen the envisioned uses of this type of fibers.

II. RESULTS

The proposed structure is composed by one circular array of thin, non-touching, dielectric cylinders. The cylinders have metal wires within the thin material. The inset of Fig. 1 shows an example of the proposed structure, while Fig. 2 (b) shows the fabricated structure.

We simulated the transmission loss of the proposed structure for various sizes of the structure, spanning the regions from 1 μm to 1 mm in wavelength. The results of the simulations, which include material loss, are shown in Fig. 1. As it is possible to see, the loss increases with decreasing wavelength. This is due to the loss induced by the metal wires. As expected, the loss of the structure is quite high in the near-IR, but it becomes very interesting in the far-IR and in the THz region. In fact, loss as low as 2.3 dB/km are achievable at wavelengths around 1 mm.

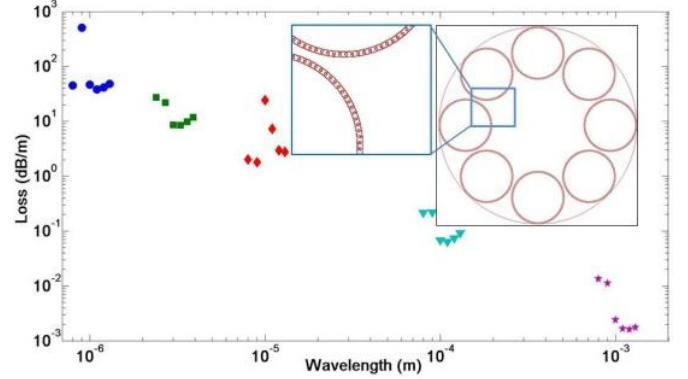


Fig. 1. Simulated transmission loss for the antiresonant metamaterial structure for various structure scaling – each colour/symbol corresponds to the same structure scaled in size to fit the investigated frequency range. Inset: schematic of the simulated structure.

We fabricated the metamaterial structure by using the fiber drawing technique [4]. We used PMMA as dielectric and Indium as metal. The realized structure is made by 6 hollow tubes, each having 40 metal wires within the tube edge. This structure differs from the simulated one for number of tubes and wires, 8 and 100 respectively in the simulated structure. The different parameters have been chosen in order to simplify the fabrication procedure. Fig. 2(b)-bottom shows the metamaterial antiresonant fabricated structure. To compare the effect of the metamaterial cladding we also realized an antiresonant structure with the same dimensions.

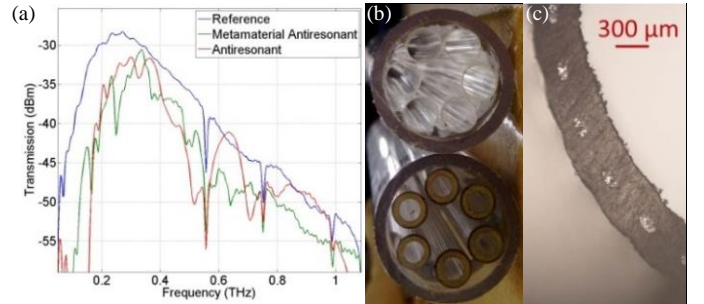


Fig. 2. (a) Measured transmission in 10 cm of the antiresonant fiber (red), in 10 cm of the metamaterial antiresonant fiber (green) and the reference THz pulse (blue). (b) The measured fibers: antiresonant fiber, top; metamaterial antiresonant fiber, bottom. Note, the metamaterial antiresonant fiber is shown with a thicker inner tube used as support during the drawing prior to being etched. (c) Microscope image of a section of the wire array tube.

Figure 2(a) shows the transmission, taken with a time domain spectroscopy (TDS) THz system, in 10 cm of the 2 fibers. The reference THz pulse, measured without any fiber between emitter and detector, is also reported. The results showed include both transmission and coupling loss. Both fibers show high transmission and as expected the antiresonant fiber shows more spectral features (transmission dips) compared to the

metamaterial one.

We simulated the realized metamaterial structure and the loss obtained at 0.3 THz is as low as 0.3 dB/m.

The THz TDS measurement allowed us to investigate the dispersion of the fiber by making a spectrogram of the time pulse and of its Fourier transform. The result is shown in Fig. 3. The higher frequency components, corresponding to a longer wavelength and, therefore to a larger mode within the fiber, experience a larger time delay, indicating a higher effective index and a larger interaction with the material. Interestingly, the dispersion is not monotonically changing with frequency. In fact, in the spectral region between 0.2 and 0.5 THz, there is an alternation of components experiencing a longer and shorter time delay. This behavior is not observed for the purely antiresonant fiber (not shown here), and might be due to resonances induced by the wires.

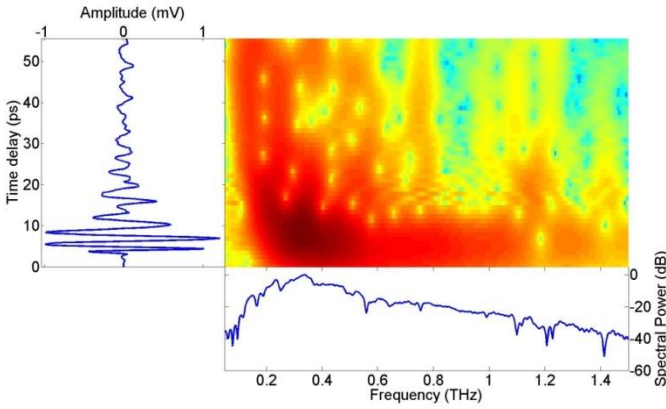


Fig. 3. Time/frequency plot for the 10 cm long metamaterial antiresonant fiber.

III. CONCLUSIONS

In conclusion, we reported a type of fiber that combines two guiding mechanisms and which has the potential for ultra-low loss in the THz frequency region. We fabricated the proposed fiber and performed preliminary transmission measurements. We will next perform accurate loss measurements and modal analysis of the fibers. Moreover, we will scale down the fiber in size to approach the far-IR region.

ACKNOWLEDGMENTS

This work was supported by the Eugen Lommel Stipend. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 708860. This work was performed in-part at The OptoFab Node of The Australian National Fabrication Facility, utilizing NCRIS and NSW State Government funding.

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